Supplementary materials - Boosting large scale osmotic power by dynamical matching of membrane ion exchange kinetics

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1 Regarding the electrodes

1.1 Unsuitability of silver electrodes for Scale-Up

The most commonly used faradaic electrodes in aqueous media are silver-silver chloride electrodes (Ag/AgCl), as used for instance by the series of results with heterogeneous membranes in [3] [15] [17] [14]. These electrodes undergo this oxidation-reduction reaction:

$$AgCl + e^- = Cl^- + Ag_s \tag{1}$$

The current regime for using these electrodes without deteriorate them must be below 20 mA cm⁻².

Regarding these studies cited, which all use these electrodes and claim the proof of scale-up, let's quickly estimate the order of magnitude of the current recovered by the electrodes with their data $P = 5 \text{ W m}^{-2}$, $S_{membrane} = 10^{-8} \text{ m}^2$, $R_{cell} = 10^4 \Omega$ and:

$$P = \frac{R_{cell}I^2}{S} \iff J = \frac{1}{S_{electrodes}} \sqrt{\frac{PS_{membrane}}{R}} \approx 10^{-3} \text{ mA cm}^{-2}$$
(2)

The current density is well below this degradation threshold.

However, let's redo the same estimation with a membrane surface of $S_{membrane} \approx 2 \text{ cm}^2 = 2.10^{-4} \text{ m}^2$ and $R_{cell} \approx 1 \Omega$, which are the orders of magnitude of our cell.

$$J = \frac{1}{S_{electrodes}} \sqrt{\frac{PS_{membrane}}{R}} \approx 10^2 \text{ mA cm}^{-2}$$
(3)

We clearly reach the degradation threshold of Ag/AgCl electrodes.

This proves that these electrodes are not suitable for system sizes beyond the square centimeter scale. It confirms that capacitive electrodes are suitable for our study and promising for blue energy harvesting. It tells also that the reported high power densities of measurement devices int the literature [3] [15] [17] [14] should not hide the feasibility of scaling them up to macroscopic levels.

Another way to approach this issue would be to calculate the mass of silver that would need to be transported to recover the engaged currents. For a power of 10 W m^{-2} , approximately 200 g m^{-2} of silver molecules would need to be transported, which is not feasible on a large scale.

1.2 Pretreatment and properties of carboneous electrodes

The capacitive carbon electrodes were cleaned by sequential 15-minute ultrasonication steps in acetone (to remove organic contaminants), ethanol (to eliminate residual acetone and polar impurities), and deionized water (to remove ionic residues and improve hydrophilicity). After cleaning, the electrodes were dried in a vacuum oven at 100°C for 1 hour, rinsed with deionized water to remove solvent residues, and stored under vacuum at 80°C overnight. No oxidation pretreatment was performed to preserve electrode stability and ensure purely capacitive behavior by avoiding pseudo-redox activity.

2 Membrane voltage under concentration gradient.

The voltage on either side of the membrane exists to compensate for differences in chemical potentials arising from different regions of electric charge concentration. The canonical mathematical model for ion transport under a chemical or electrical potential gradient brings together the mean-field Poisson-Nernst-Planck equations. The mass conservation equation is :

$$\frac{\partial c_i}{\partial t} = -\nabla \mathcal{J}_i \tag{4}$$

The Poisson equation is

$$\epsilon \Delta \Psi = -F \sum_{i} c_i z_i + \sigma \tag{5}$$

with the following notations for the mass conservation equation 4 and the Poisson equation 5 : c_i in mol m⁻³ is the concentration of species i, \mathcal{J}_i in mol m⁻² s⁻¹ is the flux density, Ψ in V is the electric potential, ϵ in F m⁻¹ is the permittivity of water, F in C mol⁻¹ is the Faraday constant, z_i in mol mol⁻¹ is the ionic charge, and σ in C m⁻³ is the fixed charge density in a given volume of electrolyte.

For macroscopic systems, the electrostatic term in Poisson's equation $\epsilon \Delta \Psi$ is negligible. Thus, equation 5 reduces to the electroneutrality condition.

$$F\sum_{i}c_{i}z_{i}+\sigma=0$$
(6)

The ionic flux is defined based on the Nernst-Planck equation, assuming the absence of advection phenomena in the longitudinal axis perpendicular to the membrane and electrodes:

$$\mathcal{J}_{i} = \underbrace{-D_{i}\nabla c_{i}}_{diffusion} - \underbrace{z_{i}D_{i}\frac{F}{RT}c_{i}\nabla\Psi}_{electromigration}$$
(7)

with R in JK^{-1} mol⁻¹ the universal gas constant and T in K the absolute temperature.

The cation exchange membranes we use contain a fixed number of charges at the ends of their side chains attached to the polymer backbone: for the Aquivion membrane used here, these are $-SO_3^{2-}$ groups. The density of these charges is on the order of $\approx 3-5$ M and is directly related to σ as defined above in the electroneutrality equation 6. Their permselectivity exceeds 95%, being 99% for Aquivion. Since cations are predominantly transported across the membrane, a depletion and accumulation on either side of it are observed, thus accompanied by a sharp variation in electrical potential. The thickness of these two diffusion layers is on the order of a few nanometers, and they are often referred to as Donnan layers. Thus, the local potential is :

$$\nabla \Psi = -\frac{RT}{F} \left(\frac{\sum_{i} z_{i} D_{i} \nabla c_{i}}{\sum_{i} z_{i}^{2} D_{i} c_{i}} \right)$$
(8)

This is non-linear and cannot be solved analytically: we are only interested in the potential difference between the two ends of the two diffusion layers, so by integrating, we obtain the membrane potential difference, which is the sum of the two Donnan contributions on each side.

$$\Delta \Phi_m = \frac{RT}{F} \ln \frac{c_+}{c_-} \tag{9}$$

with c_+ and c_- the high-salt and low-salt concentration.

The numerical application yields for our gradient of 100 ($c_{+} = 1M$ and $c_{-} = 10$ mM) is :

$$\Delta \Phi_m = 118 \mathrm{mV} \tag{10}$$

3 Influence of temperature

3.1 Material and methods

For the temperature study, high-power heating plates were used to heat the high-salt and low-salt solutions in upstream reservoirs. The temperature was recorded both upstream and downstream of the cell to ensure accurate monitoring. Sufficient time was allowed for the entire system—including the reservoirs, tubing, and the cell itself—to



Figure 1: Temperature-dependent performance of the system, evaluated at four temperatures $(25 \,^{\circ}\text{C}, 40 \,^{\circ}\text{C}, 60 \,^{\circ}\text{C}, and 80 \,^{\circ}\text{C})$. (a) Open Circuit Voltage (OCV) as a function of time, showing a decrease in membrane response time from 10 s at room temperature to 6 s at 80 $^{\circ}\text{C}$. (b) Potentiostatic Electrochemical Impedance Spectroscopy (PEIS) Nyquist plots (c) Harvested power as a function of temperature, demonstrating a steady increase due to the decreasing membrane response time.

reach thermal equilibrium before initiating measurements. This ensured that all components were fully thermostated to the target temperature, providing stable and reproducible conditions throughout the experiments.

The experimental setup and parameters used for the temperature study were identical to those described in the main text. High-salt ($c_{+} = 1 \text{ M}$) and low-salt ($c_{-} = 10 \text{ mM}$) solutions were prepared with sodium chloride (99%, Sigma-Aldrich) and ultrapure water (Milli-Q, Millipore, $18.2 \text{ M}\Omega \cdot \text{cm}$ at 25 °C). The pH of the solutions was 7, with conductivities of 86.5 mS/cm and 1.22 mS/cm, respectively, measured using a Hannah Instruments HI2030-02. Flow rates were kept constant at 70 mL/min for both solutions.

In the same way, electrochemical measurements were performed using a potentiostat (Biologic, VSP) in a twoelectrode configuration connected to the graphite current collectors. Open Circuit Voltage (OCV), Potentiostatic Electrochemical Impedance Spectroscopy (PEIS), and cyclic voltammetry (CV) were conducted and presented figure 1. For power measurements, a load resistance was used to record the voltage drop, allowing the calculation of current and power via Ohm's law.

3.2 Results and discussion

Figure 1a shows the Open Circuit Voltage (OCV) measurements as a function of time for different temperatures, following the same protocol as explained in the main text. Here, t = 0 s corresponds to the moment when the circuit is opened, and the flows of high-salt and low-salt solutions are reversed after several minutes of short-circuiting the cell.

The results indicate that the membrane's response time τ_m decreases with increasing temperature. At room temperature (~ 25 °C), the voltage drop E, and therefore the membrane takes a longer time to reach steady state, whereas at (~ 80 °C) this time is decreased.

This behavior reflects the diffusional properties of the cation exchange membrane (CEM), which are known to improve with temperature due to enhanced ionic mobility and reduced viscosity of the solutions.

As anticipated, extensively analyzed, and thoroughly discussed in the main text, the reduction in the membrane response time, particularly when compared to the capacitive response time of the electrodes, facilitates a faster establishment of the salinity gradient across the membrane. This, in turn, leads to an increase in power output as the temperature rises.

Figure 1b shows the Potentiostatic Electrochemical Impedance Spectroscopy (PEIS) results. At first approximation, the electrochemical properties of the electrodes appear largely unaffected by the change in temperature. However, at 80 °C, the Nyquist plots reveal a capacitive behavior, characterized by the near-vertical shape of the curve, which is following a diffusive regime nearly absent.

As expected, due to this temperature dependence of the membrane response time decreasing and the capacitive response time remaining approximately constant, experimental power measurement of Figure 1c shows that the harvested power increases with temperature, reaching $5.94 \,\mathrm{W m^{-2}}$



Figure 2: Cyclic voltammetry (CV) of the electrochemical system over 300 cycles, performed under static conditions without electrolyte flow and assembled identically to the power measurement setup. The measurements were conducted at a scan rate of 1 mV/s between -500mV and 500mV.

4 Long-Term Electrochemical Stability

Cyclic voltammetry (CV) tests over 300 cycles were performed without electrolyte flow, under the same assembly conditions as the power measurements, with Aquivion 980 membrane. This is presented figure 2. The rectangular shape observed throughout confirm purely capacitive behavior, with no evidence of redox or pseudo-redox reactions. Electrode capacitance remained constant over all cycles, demonstrating excellent resistance to degradation. These results validate the durability of our capacitive osmotic cell for extended energy harvesting applications.

5 Maximum power under general forcing

The model of the equivalent circuit of the osmotic cell and the average power recovered over a reversal cycle through the load presented in the main article assumed sinusoidal forcing. We introduce now the dimensionless parameters in Table 1 which will be used in the following section.

5.1 Sinusoidal forcing

The average power formula for sinusoidal forcing, already written in the main article, is recalled here.

$$\langle \mathscr{P} \rangle = \mathscr{P}_0 \frac{y\alpha^2}{\left[1 - \alpha^2(1 + y - \gamma)\beta\right]^2 + \alpha^2\left[1 + y + \beta\right]^2} \tag{11}$$

5.2 Square-like forcing

The experiments are rather performed under square-like forcing, where the concentration gradient is switched abruptly every time T_s , with period $T = 2T_s$.



Figure 3: Maximum average power $\langle \mathscr{P} \rangle_{max} = \langle \mathscr{P} \rangle (y = y_{max})$ plotted against the switching time $\frac{T_s}{\tau_{cell}}$ for different types of forcing. The power is scaled by $\mathscr{P}_0 = \frac{1}{8} \frac{\Delta V_0}{R_{cell}}$ (as defined in the main text). Plots with squares corresponds to square forcing of equation 17. Plots with circles are sinusoidal forcing of equation 17. Plots with triangles are sawtooth forcing of equation 19. For each forcing regime, several $\beta = \frac{\tau_m}{\tau_{cell}}$ values were shown. The β values are identified by the coloured bar on the right.

Name	Definition	
R_{cell}	$R_{cell} = R_{res} + R_{el} + R_m$	the overall resistance of the cell
$ au_{cell}$	$\tau_{cell} = R_{cell}C$	the capacitive time constant of the cell
y	$y = \frac{R_{load}}{R_{cell}}$	the dimensionless load resistance
γ	$\gamma = \frac{R_m}{R_{cell}}$	the dimensionless membrane resistance
α	$\alpha = \omega \tau_{cell}$	the dimensionless pulsation
α_k	$\alpha_k = \omega_k \tau_{cell}$	the dimensionless pulsation of Fourier mode \boldsymbol{k}
$oldsymbol{eta}$	$eta = rac{ au_m}{ au_{cell}}$	the balance between diffusive relaxation time of the membrane and the capaci- tive time

Table 1: Definitions of dimensionless parameters

The instantaneous power writes, with the notation used in the equivalent circuit presented in the main article :

$$\mathcal{P}(t) = R_{load} i^2(t) \tag{12}$$

In order to calculate the maximum power, one should calculate the average power over a period. To be more consistent with the physics involved in the membrane, on either side of which a voltage is created by the difference in concentration, as we saw in section 2, we use a Thevenin generator model rather than the Norton model presented in the main article. The membrane is modelled with $\Delta V_0(t)$ and its low-pass filter impedance with its dynamic response time constant $\tau_m : \frac{R_m}{1+j\omega\tau_m}$. Thus, we assume a square-like forcing for $\Delta V_0(t)$, and write it as a Fourier serie :

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$$\Delta V_0(t) = \Delta V_0 \sum_{k=1}^{\infty} \frac{4}{\pi} \frac{\sin(2k-1)\omega t}{2k-1}$$
(13)

with $\omega = \frac{2\pi}{T} = \frac{\pi}{T_s}$. We introduce the Fourier modes $\omega_k = (2k-1)\omega$ and $\Delta V_k = \Delta V_0 \frac{4}{\pi} \frac{1}{2k-1}$ The current through the load i(t) was already calculated in the main article and for a given frequency ω , the k mode for the current i_k is therefore :

$$\underline{i}_{k} = \frac{\Delta V_{k} j \omega_{k} C (1 + j \tau_{m} \omega_{k})}{1 - \omega_{k}^{2} (R_{res} + R_{el} + R_{load}) C \tau_{m} + j \omega_{k} \left[(R_{res} + R_{el} + R_{m} + R_{load}) C + \tau_{m} \right]}$$
(14)

The time-average power can thus be witten, using the Parceval theorem :

$$<\mathcal{P}> = < R_{load}i^{2}(t) > = \frac{1}{2}R_{load}\sum_{k=1}^{\infty} \frac{\Delta V_{k}^{2}C^{2}\omega_{k}^{2}(1+\tau_{m}^{2}\omega_{k}^{2})}{\left[1-\omega_{k}^{2}(R_{res}+R_{el}+R_{load})C\tau_{m}\right]^{2}+\omega_{k}^{2}\left[(R_{res}+R_{el}+R_{m}+R_{load})C+\tau_{m}\right]^{2}}$$
(15)

so that the average power is :

$$<\mathcal{P}> = \frac{1}{2R_{cell}} \sum_{k=1}^{\infty} \frac{y \Delta V_k^2 \alpha_k^2 (1+\beta^2 \alpha_k^2)}{\left[1-\beta \alpha_k^2 (1+y-\gamma)\right]^2 + \alpha_k^2 \left[1+y+\beta\right]^2}$$
(16)

Since $\alpha_k = \alpha(2k-1)$ and $\Delta V_k = \Delta V_0 \frac{4}{\pi} \frac{1}{2k-1}$, a proper coincidence is that $\alpha_k^2 \Delta V_k^2 = (\frac{4}{\pi} \alpha \Delta V_0)^2$, independent of k. Hence :

$$\langle \mathscr{P} \rangle = \frac{y(\frac{4}{\pi}\alpha\Delta V_0)^2}{2R_{cell}} \sum_{k=1}^{\infty} \frac{1+\beta^2\alpha^2(2k-1)^2}{\left[1-\beta\alpha^2(1+y-\gamma)(2k-1)^2\right]^2+\alpha^2(1+y+\beta)^2(2k-1)^2}$$
(17)

This serie can be calculated analytically but it's not convenient to use it.

However, we can find for given β and α the extremum of the power $\langle \mathscr{P} \rangle (y)$ versus $y = \frac{R_{load}}{R_{cell}}$ and then compute the corresponding maximum power $\langle \mathscr{P} \rangle_{max} = \langle \mathscr{P} \rangle (y = y_{max})$. The outcome is shown in 3 for $\langle \mathscr{P} \rangle_{max}$, normalized by $\mathscr{P}_0 = \frac{\Delta V_0^2}{2R_{cell}}$, versus the normalized switching time $\frac{1}{\alpha} = \frac{1}{\omega \tau_{cell}} = \frac{1}{\pi} \frac{T_s}{\tau_{cell}}$, to be consistent with the plot of the experimental results of the main article.

5.3 Sawtooth forcing

This framework can be used to predict the maximum power for any time-dependant signal. The concentration gradient is switched every time T_s , with period $T = 2T_s$. Let's have a look of what happend if the voltage at the membrane follows a sawtooth pattern :

$$\Delta V_0(t) = \Delta V_0 \sum_{k=1}^{\infty} \frac{2(-1)^{k+1}}{\pi k} \sin k\omega t$$
(18)

so that we define as previously : $\Delta V_k = \frac{2(-1)^k}{\pi k}$, and again, $(\alpha_k \Delta V_k)^2$ is independent of k. Starting again from 16, we can thus write :

$$<\mathscr{P}>=\frac{y(\frac{2}{\pi}\Delta V_{0}\alpha)^{2}}{2R_{cell}}\sum_{k=1}^{\infty}\frac{(-1)^{k}(1+\beta^{2}\alpha^{2}k^{2})}{\left[1-\beta\alpha^{2}k^{2}(1+y-\gamma)\right]^{2}+\alpha^{2}k^{2}\left[1+y+\beta\right]^{2}}$$
(19)

Again, we can calculate the serie analytically but it's not convenient. Thus, we compute the corresponding maximum power $\langle \mathcal{P} \rangle_{max} = \langle \mathcal{P} \rangle (y = y_{max})$ and plot it for different β values in 3.

5.4 Behaviour of the different forcings.

The figure 3 presents the maximum average power, $\langle \mathscr{P} \rangle_{\text{max}} = \langle \mathscr{P} \rangle (y = y_{\text{max}})$, plotted against the switching time, $\frac{T_s}{\tau_{\text{cell}}}$, for different types of forcing. The power values have been scaled by $\mathscr{P}_0 = \frac{1}{8} \frac{\Delta V_0}{R_{\text{cell}}}$, providing a normalized basis for comparison across different forcing regimes.

For each type of forcing, multiple values of $\beta = \frac{\tau_m}{\tau_{\text{cell}}}$ are displayed, with the β values indicated by the colored bar on the right. From a physical standpoint, the parameter β characterizes the relative relaxation time of membrane dynamics compared to the capacitive dynamics. A higher β value is associated with slower membrane dynamics while a lower β value, indicates faster internal relaxation of the membrane dynamics.

Plots with squares represent the square forcing described by equation 17. Note that the power is a decreasing function of T_s . In this case, the maximum attainable power is achieved at short switching times. It is found to increase with β . Similar behavior occurs with the sawtooth signal (plotted as triangles), as described by equation 19. While this regime also reaches its peak power at short switching times, the maximum power achieved is much lower than that of the square forcing.

The behavior of these drivings, which both involves a discontinuity versus time, differs considerably from the smooth sinusoidal forcing, as described in equation 11. The shape of the power curve for sinusoidal forcing is non-monotonous versus T_s and shows that in this case the maximum power is reached at increasingly longer switching times as β increases (indicating slower membrane dynamics). Furthermore, the maximum power decreases as the membrane dynamics slows down, illustrating the key influence of β on our osmotic cell performance. As discussed in the main text, this trend is in agreement with experimental observations of the main article.

This indicates that the forcing that best describes our experiments is the sinusoidal forcing and confirms once again that the β parameter is key in the harvested power, confirming that the dynamics of the membrane does govern the ability to achieve high power harvesting.

5.5 Similar studies performance

We present here a comparative table of the main results reported in the literature for the RED and CRED techniques, which use commercial polymer membranes. Excluded are membranes made of new 2D materials, and results obtained with nanofluidic systems such as nanopores and nanotubes.

Technology	Membrane	c_+	с_	Gradient	Author	Power (W/m ²)	Ref.
RED	polythene with cross-linked polystyrene	0,507	0,017	30	Pattle	0,2	[10]
RED	PECH	0,507	0,017	30	Guler	$1,\!2$	[6]
RED	PSDB grafted on PMP	1	$_{0,1}$	10	Golubenko	$0,\!67$	[4]
RED	sPVA (5 wt %) / sPPO	$0,\!5$	$0,\!017$	29	Zhang	$0,\!46$	[13]
RED	SPEEK/PECH	$0,\!513$	$0,\!017$	30	Güler	$1,\!3$	[5]
RED	QPS-QPPO	$0,\!599$	0,00856	70	Lee	1,82	[9]
RED	DABCO-bound AEM	$0,\!5$	$0,\!017$	29	Choi	$1,\!52$	[2]
RED	Fe2O3-SO42- modified SPPO	$0,\!5$	0,017	29	Hong	1,3	[7]
RED	AC treated SPPO	$0,\!599$	0,017	35	Lee	1,34	[8]
RED	Neosepta $\rm CMX/AMX$	0,508	$0,\!017$	30	Vermaas	1,02	[11]
CRED	Neosepta $\rm CMX/AMX$	0,508	$0,\!017$	30	Vermaas	$0,\!95$	[12]
CRED	Nafion 211	1,71	$0,\!0171$	100	Brahmi	1,38	[1]
CRED	Selemion CMV	$0,\!5$	$0,\!017$	29	Zhu	$0,\!95$	[16]
CRED	Aquivion 870	1	0,01	100	Chapuis- Bocquet (this work)	5,3	

References

- Youcef Brahmi and Annie Colin. New membrane and electrode assembly concept to improve salinity energy harvesting. <u>Energy Convers. Manag.</u>, 254(115297):115297, February 2022.
- [2] Jiyeon Choi, Seungcheol Yang, Nam-Jo Jeong, Hanki Kim, and Won-Sik Kim. Fabrication of an anionexchange membrane by pore-filling using catechol-1,4-diazabicyclo-[2,2,2]octane coating and its application to reverse electrodialysis. Langmuir, 34(37):10837–10846, September 2018.
- [3] Jun Gao, Wei Guo, Dan Feng, Huanting Wang, Dongyuan Zhao, and Lei Jiang. High-performance ionic diode membrane for salinity gradient power generation. <u>Journal of the American Chemical Society</u>, 136(35):12265– 12272. Publisher: American Chemical Society.
- [4] D V Golubenko, B Van der Bruggen, and A B Yaroslavtsev. Ion exchange membranes based on radiationinduced grafted functionalized polystyrene for high-performance reverse electrodialysis. J. Power Sources, 511(230460):230460, November 2021.
- [5] Enver Güler, Rianne Elizen, David A Vermaas, Michel Saakes, and Kitty Nijmeijer. Performance-determining membrane properties in reverse electrodialysis. J. Memb. Sci., 446:266–276, November 2013.
- [6] Enver Guler, Yali Zhang, Michel Saakes, and Kitty Nijmeijer. Tailor-made anion-exchange membranes for salinity gradient power generation using reverse electrodialysis. <u>ChemSusChem</u>, 5(11):2262–2270, November 2012.
- [7] Jin Gi Hong and Yongsheng Chen. Nanocomposite reverse electrodialysis (RED) ion-exchange membranes for salinity gradient power generation. J. Memb. Sci., 460:139–147, June 2014.

- [8] Ju-Young Lee, Jae-Hun Kim, Ju-Hyuk Lee, Seok Kim, and Seung-Hyeon Moon. Morphologically aligned cationexchange membranes by a pulsed electric field for reverse electrodialysis. <u>Environ. Sci. Technol.</u>, 49(14):8872– 8877, July 2015.
- [9] Young Ju Lee, Min Suc Cha, Seong-Geun Oh, Soonyong So, Tae-Ho Kim, Won Sun Ryoo, Young Taik Hong, and Jang Yong Lee. Reinforced anion exchange membrane based on thermal cross-linking method with outstanding cell performance for reverse electrodialysis. RSC Adv., 9(47):27500–27509, August 2019.
- [10] R E Pattle. Production of electric power by mixing fresh and salt water in the hydroelectric pile. <u>Nature</u>, 174(4431):660–660, October 1954.
- [11] David A Vermaas, Suman Bajracharya, Bruno Bastos Sales, Michel Saakes, Bert Hamelers, and Kitty Nijmeijer. Clean energy generation using capacitive electrodes in reverse electrodialysis. <u>Energy Environ. Sci.</u>, 6(2):643–651, 2013.
- [12] David A Vermaas, Suman Bajracharya, Bruno Bastos Sales, Michel Saakes, Bert Hamelers, and Kitty Nijmeijer. Clean energy generation using capacitive electrodes in reverse electrodialysis. <u>Energy Environ. Sci.</u>, 6(2):643–651, 2013.
- [13] Hongguo Zhang, Di Jiang, Bopeng Zhang, Jin Gi Hong, and Yongsheng Chen. A novel hybrid poly (vinyl alcohol) (pva)/poly (2,6-dimethyl-1,4-phenylene oxide) (ppo) membranes for reverse electrodialysis power system. Electrochimica Acta, 239:65–73, 2017.
- [14] Zhen Zhang, Li He, Congcong Zhu, Yongchao Qian, Liping Wen, and Lei Jiang. Improved osmotic energy conversion in heterogeneous membrane boosted by three-dimensional hydrogel interface. <u>Nature Communications</u>, 11(1):875, 2020.
- [15] Zhen Zhang, Xin Sui, Pei Li, Ganhua Xie, Xiang-Yu Kong, Kai Xiao, Longcheng Gao, Liping Wen, and Lei Jiang. Ultrathin and ion-selective janus membranes for high-performance osmotic energy conversion. <u>Journal</u> of the American Chemical Society, 139(26):8905–8914. Publisher: American Chemical Society.
- [16] Haihui Zhu, Wangwang Xu, Guangcai Tan, Elizabeth Whiddon, Ying Wang, Christopher G Arges, and Xiuping Zhu. Carbonized peat moss electrodes for efficient salinity gradient energy recovery in a capacitive concentration flow cell. Electrochim. Acta, 294:240–248, January 2019.
- [17] Xuanbo Zhu, Junran Hao, Bin Bao, Yahong Zhou, Haibo Zhang, Jinhui Pang, Zhenhua Jiang, and Lei Jiang. Unique ion rectification in hypersaline environment: A high-performance and sustainable power generator system. <u>Science Advances</u>, 4(10):eaau1665. Publisher: American Association for the Advancement of Science.